

Path Loss Models for Low-Height Mobiles in Forest and Urban

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Abstract This paper presents path loss measurements at 2.1 GHz in forest and urban areas. Empirical path loss models have been presented for low-height dual-mobility channels. Three test scenarios are considered for the transmitter (Tx) and receiver (Rx) placed inside the test vehicle or on a test cart pushed at walking speed. Based on measurements, the in-leaf and single-slope path loss models are presented. The path loss exponents for the dual-mobility channels are found to be between 2.1 and 3.4 in urban and 8.0 in forest, with higher reference when antennas are placed inside the vehicle.

Keywords Dual-mobility · Vehicle-to-vehicle · Vehicle-to-walk · Dense scatter · Path loss

1 Introduction

In mobile ad hoc wireless networks, mobility is often required for nodes or terminals. Channels in these dual-mobility (DM) are different from those in conventional cellular communication systems, since the Tx and Rx are both in motion, and the antennas at the Tx and Rx are closer to ground level. Intensive measurements for vehicle-to-vehicle (V2V) channels, which are one type of DM channels are conducted in various highway, suburban, rural road, and some application-specific scenarios, such as traffic congestion, at 5 GHz and 700 MHz. The path loss, power-delay profiles, and delay-doppler spectra have been analyzed, e.g., [1–3]. The two-ray model (2-Ray) [4], which was originally proposed for cellular communications, is suggested to represent the path loss in rural V2V channels [5]

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and confirmed by measurements with a line-of-sight (LOS) environment [6]. In most V2V channel measurements, transmitter and/or receiver antennas are usually placed on the roof of the test vehicles. However, in many applications of DM communications, the mobile units (and their antennas) are often inside a vehicle traveling on road, or inside a pocket or bag carried by a pedestrian walking alongside road, parking lots, or woody/forest areas. Available channel measurements and models for these types of DM channels are found to be limited, although the vehicle penetration loss for antennas inside a vehicle is studied by measurements in the range of 100–2400 MHz [7, 8].

A variety of path loss models have been developed for stationary channels in forest environments [9–13], to account for the excessive attenuation beyond that predicted by free space or 2-Ray propagation. The detailed specifications for these models are listed as follows:

- COST235 model [9]: $PL_{\text{COST}} = 15.6 f^{-0.009} d^{0.26}$ in-leaf,
- Weissberger [10]: $PL_{\text{W}} = 1.33 f^{0.284} d^{0.588}$, $14 \text{ m} < d < 400 \text{ m}$,
- ITU-R model [11]: $PL_{\text{ITU-R}} = 0.2 f^{0.3} d^{0.6}$,
- Fitted ITU-Recommendation (FITU-R) model [12]: $PL_{\text{FITU-R}} = 0.39 f^{0.39} d^{0.25}$ in-leaf
- Lateral ITU-R model [13]: $PL_{\text{LITU-R}} = 0.48 f^{0.43} d^{0.13}$,

where the frequency f is in MHz for all models, except for the PL_{W} model, where the frequency is in GHz. This concludes that the path loss in general can be expressed as, $PL = c_1 f^{c_2} d^{c_3}$, where PL is the path loss in dB, f is the radio frequency, and $c_i, i = 1, 2, 3$ are constants related to the frequency and test environments.

The received signal power at the receiver P_r in dBm is generally expressed as $P_r = P_t - PL + S + \Omega$, where the transmitted power P_t is in dBm, the path loss PL is in dB, the power of shadowing S is in dB, and the power of small scale fading Ω [4] is in dB. The small-scale fading power is first filtered out from P_r by applying a moving average window [4] over the distance. This results in a local average that consists of path loss and shadowing component. The shadowing component can be extracted by subtracting the estimated path loss from the local average using the single-slope regression formulae or any model for path loss.

The remainder of this paper is organized as follows: Sect. 2 introduces measurement setup and test scenarios. Channel models for path loss based on measured received signal power are presented in Sect. 3. Section 4 concludes the paper with a summary of observations.

2 Measurement Setup and Test Scenarios

Measurements reported in this work are different from those in the literature: (1) new setups, antenna placements are considered: (a) inside-vehicle-to-inside-vehicle (IV2IV), where the antennas of both Tx and Rx are placed inside the test vehicles; and (b) inside-vehicle-to-walk (IV2W), where the Tx antenna is placed inside the vehicle, and the Rx antenna is placed on a cart pushed by a tester at walking speed, where all similar V2V campaigns have antennas mounted on rooftops; (2) new frequency 2.1 GHz, which is obviously intended for cellular extensions of coverage and different than 5 GHz applications. In addition to the 2G and cellular use of 2.1 GHz in Europe and US [4], it is an option for long term evolution-advanced (LTE-Advanced) [14]; (3) low speeds as low as 20 mi/hr for vehicles and 2–3 mi/hr for walking, where most V2V campaigns are

conducted under LOS conditions and at much higher speeds. (4) measurements are collected at farther Tx–Rx separations than ones in [5]; and (5) collected measurements in forest, measurements and models for DM channels in woody or forest areas are not found in the literature [9, 10, 15, 16].

Measurements campaign was held in northern New Jersey in the month of June. Tests were conducted in woody/forest and urban areas with a mix of dense trees, storied buildings, street signs, and corners, where heavy diffraction and dense scattering of radio signals were likely to occur [4]. In both areas, trees and grass were at their full growth. Before starting our channel measurement, both areas were scanned to ensure that the frequency of 2110.2 MHz was not being used. Low received power of -121 dBm was recorded in both areas which confirmed areas were clean. The receiver had a sensitivity threshold of -135 dBm and was set to 50 KHz bandwidth. Test equipment included a Tx Berkeley Varitronics System Gator class with an omni antenna with 1 dBi gain and 1.5 W transmitting power that transmitted a continuous narrow-band unmodulated wave, and Invex.NxG i.Scan Rx System Andrew Solutions with a 0 dBi gain omni antenna. Figure 1 shows measurements setup for both Tx and Rx.

2.1 Scenario 1—IV2IV Forest

In this scenario, the Tx and Rx antennas were vertically placed inside the test vehicles at heights of, respectively, 1.5 meters (m) and 1.25 m above the ground level. The test route in a woody/forest area is shown in Fig. 2. The Tx and Rx traveled away or towards each other at an angle, such as 90° out $\leftarrow \uparrow$ and 90° in $\leftarrow \downarrow$, marked by the dotted and dash-dotted lines. There was no visibility between the Tx and Rx due to the large-diameter trees in between.

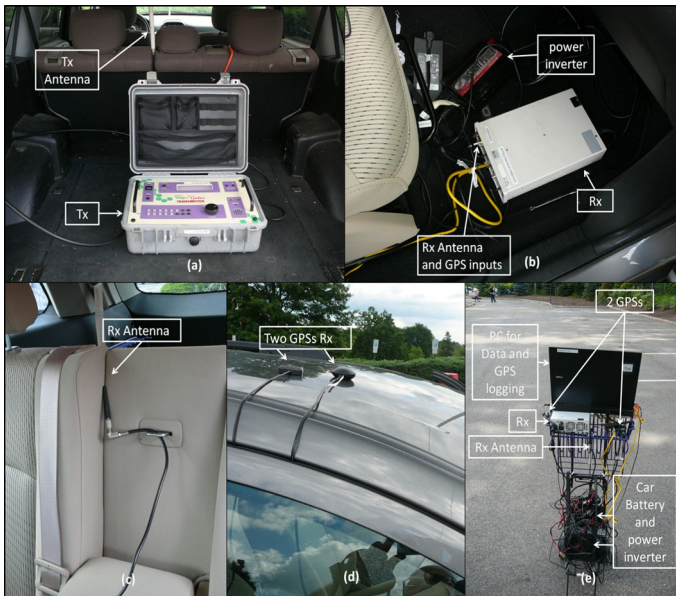


Fig. 1 a and b Tx and Rx inside test vehicle; c Rx antenna inside test vehicle; d GPSs for Rx on roof of vehicle; e Rx on test cart



Fig. 2 Test area in the forest environment for Scenario 1

2.2 Scenario 2—IV2IV Urban

In this scenario, the test equipment and antenna positions were configured the same as in Scenario 1. The test areas were on urban streets, as shown in Fig. 3. As urban areas are determined by the geography of the land and buildings distribution on land, visibility from the Tx to Rx was not always guaranteed. We collected two sets of measurements, visibility existed and not existed, in order to obtain more accurate channel models.

2.2.1 Scenario 2a—Without LOS

Three test routes were configured as shown in the upper half of Fig. 3 by dotted, dashed, and dash-dotted lines. The Tx traveled on a T-shaped street at street speed along with the traffic, and the Rx traveled on a smaller street in a parking lot at a speed of 5 ~ 20 mi/hr. The Tx and Rx traveled in the same or opposite direction, and there was no visibility between them.

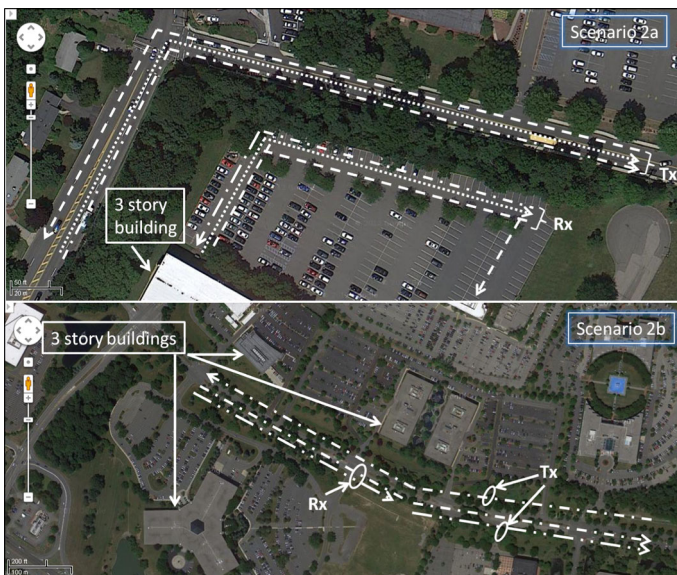


Fig. 3 Test area in the urban environment for Scenario 2

2.2.2 Scenario 2b—With LOS

Test streets are shown in the lower half of Fig. 3. The Tx and Rx traveled on a two-way urban street with two lanes in each direction. Groups of two- or three-story buildings were found 20–40 m away from the curbs. A 10 m wide divider or median strip of trees, bushes, and grass was in the middle of the street. The LOS between the Tx and Rx existed when they were moving in the same direction, $\text{Tx} \leftarrow \text{Rx}$, and partially not existed in opposite directions, $\text{Tx} \rightarrow \leftarrow \text{Rx}$, due to the trees and grass in between them.

2.3 Scenario 3—IV2W Urban

As illustrated in Fig. 1e, the Tx was placed inside the test vehicle with the antenna 1.5 m above the ground. The Rx was placed on the test cart with the antenna 1 m above the ground. The test area for Scenario 3 is shown in Fig. 4, where the Tx traveled at 20~35 mi/hr on the streets marked by dash-dotted and dotted lines, and the Rx placed on the cart which was pushed at a pedestrian speed 2~3 mi/hr in the side walks marked by dash-dotted and dotted lines. The LOS between the Tx and Rx existed for most of samples collected, except for those when the LOS was blocked or partially blocked by traffic, trees, or the tester pushing the cart.

3 Path Loss Models

To extract the local average from the received signal power, we followed the guideline in [5]. We used a 3 m moving average window, the window size is usually 5~40 times the radio wavelength of the frequency [5], to filter out the fast variations (small-scale fading) components from the received signal power. Analysis on other window sizes showed that smaller windows picked up part of the small-scale fading components, while larger failed to follow the local average in the received signals. As a result, the 3 m window which corresponds to 21.1 times the wavelength of 2.1 GHz was found appropriate size and used in our paper.

Next, the local average was split into path loss and shadowing components by applying regression models with a single-slope or in-leaf path loss model as we show in this section. The log-normal probability density function for shadowing is given by Eq. (5.59) in [17]: $f_s(s) = \frac{10}{\sqrt{2\pi\kappa s \ln(10)}} \exp\left(-\frac{(10\log s - \mu)^2}{2\kappa^2}\right)$, where s is the power in watts, $\ln(\cdot)$ is the

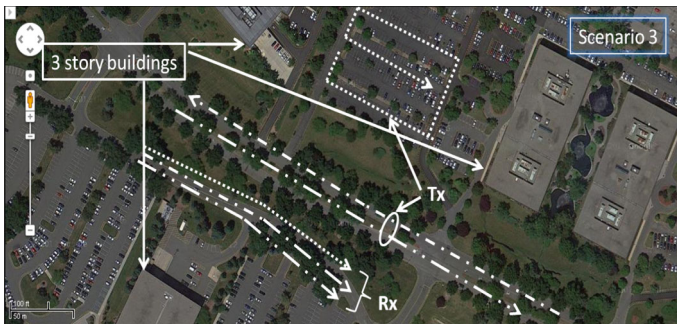


Fig. 4 Test area in the urban environment for Scenario 3

Table 1 Summary of path loss models: single-slope $(n, PL(d_0), \kappa)$ and in-leaf c_1, c_2, c_3

Scenario	Heights (h_t, h_r) , Tx–Rx range	Path loss models
Scenario 1	1.5 m, 1.25 m, $80 < d < 320$ m	In-leaf: 0.77, 0.24, 0.41 Single-slope: 8.0, 65.5, 3.57 dB
Scenario 2a	1.5 m, 1.25 m, $10 < d < 425$ m	Single-slope: 2.11, 88.43, 4.5 dB
Scenario 2b	1.5 m, 1.25 m, $10 < d < 450$ m	Single-slope: 2.46, 77.76, 4.8 dB
Scenario 3	1.5 m, 1.0 m, $10 < d < 325$ m	Single-slope: 3.44, 72.33, 3.81 dB

natural logarithm of base e , $\log(\cdot)$ is the logarithm of base 10, $\mu = \mathbb{E}[S]$ is the mean, and $\kappa^2 = \mathbb{V}[S]$ is the variance. By estimating the average and standard deviation of shadowing component, the estimated values for κ are listed in Table 1. The estimated values for μ were found to be all 0 dB. This aligns with the reported 0 dB values at 5.9 GHz frequency in [6, 18], but with antennas on the roof of vehicles.

3.1 Scenario 1

The proposed path loss model in Scenario 1, taking into account the 2-Ray model [4], has the following form, $PL = c_1 f^{c_2} d^{c_3} + 40 \log d - 20 \log h_t - 20 \log h_r$, where h_t and h_r are the antenna heights of Tx and Rx, respectively, and $c_i, i = 1, \dots, 3$ are to be estimated by applying the least square fitting to the measurements, the in-leaf path loss for Scenario 1 is expressed by

$$PL = 0.77 \times f^{0.24} \times d^{0.41} + 4 \times 10 \log d - 20 \log h_t - 20 \log h_r \tag{1}$$

Vehicle loss (VL) was found to be 3.8–9.5 at 1.8 GHz, and 5.3–13.8 at 2.4 GHz in [8]. In our campaign, a VL of 5.4 dB was measured and added to existing models listed in the introduction section for fair comparisons. For Scenario 1, the in-leaf path loss model is studied and compared with existing stationary models. Furthermore, the regression models are applied with single-slope [19, 20] for all scenarios. Table 1 summarizes the proposed models. A single-slope model has a simple form:

$$PL(d) = PL(d_0) + 10n \log(d/d_0) \tag{2}$$

where $PL(d)$ is the path loss at the separation distance d between the Tx and Rx, \log is the logarithm of base 10, and $PL(d_0) = P_t - P_r(d_0)$ characterizes the path loss at the reference distance d_0 . The reference distance is often chosen as 1 m for indoor, 100 m for micro cell, and 1 km for urban mobile systems [4]. In this paper, $d_0 = 100$ m is chosen for Scenario 1, as the minimum Tx–Rx separation was 90 m for this scenario, and $d_0 = 10$ m is used for the rest of scenarios. The parameters in (2) are estimated from measurements.

Table 1 lists the obtained in-leaf path loss model in (1), and single-slope models in (2) for different test scenarios. It is worth to note that $2 \times VL$ for Scenarios 1 and 2 and VL for Scenario 3 can be subtracted accordingly from $PL(d_0)$ in proposed models to give estimations of having the Tx and Rx antennas on rooftop or outside the vehicle. Figure 5 plots proposed models and existing empirical path loss models in forest environments. Both 2-Ray model and VL are included in existing models in the plot. Figure 5 indicates that

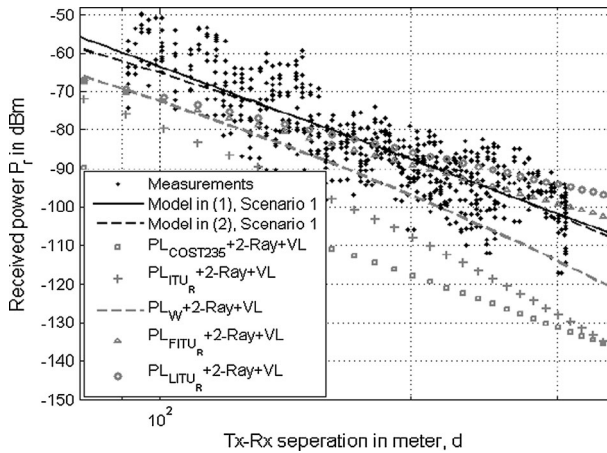


Fig. 5 Received power and path loss models for Scenario 1

proposed models provide more accurate estimates for the path loss than the existing models. The PL_{LITU-R} model seems to provide the best performance among these existing models. To compare with existing models, we calculate the mean square error (MSE) of the models as $\frac{\sum_{i=1}^N |\Delta_i|^2}{N}$, where N is the total number of measurements, and Δ_i is the difference between measured received power and estimated path loss by the models for the i th sample. The MSE for the regression model in (2) shows improvement of 1.4 dB over the closest fitting model which found to be PL_{LITU-R} , while the proposed path loss model in (1) shows improvement of 1.85 dB over PL_{LITU-R} . To evaluate the goodness-of-fit, we used the coefficient of determination $r^2 = \frac{\sum_i (y_i - \bar{y})^2}{\sum_i (y_i - \hat{y}_i)^2}$ [21] where y_i , \hat{y}_i and \bar{y} are respectively the measured, predicted using model, and the mean of the measured data. The coefficient of determination is a good measure for both linear and non-linear relationships [21]. The closer the value of r^2 to 1, the better the fitting model to measured data. It was observed that r^2 was respectively 0.9, 0.8, and 0.2 for the regression model in (2), the proposed path loss model in (1), and the best existing PL_{LITU-R} model. It is noticed that the coefficient of determination for the regression model in (2) shows a slightly better fit to measurements than the proposed model in (1).

3.2 Scenario 2

Depending on the availability of LOS between the Tx and Rx, two data sets are collected: Scenario 2a—without LOS and Scenario 2b—with LOS. We note the following observations:

- Scenario 2a: Measurements of the received signal power are shown in Fig. 6 with the proposed path loss model. The path loss exponent in the single-slope model is found as $n = 2.11$, and the received power at reference distance is $P_r(d_0) = -56.43$ dBm.
- Scenario 2b: As shown in Fig. 7, the path loss exponent is $n = 2.46$ and $P_r(d_0) = -45.76$ dBm, The path loss exponent is found to be close to those observed at 5.9 GHz in [18], where the exponent was found in the range of 2.32 to 2.75 dB for data sets collected (data set 1 was collected in summer and data set 2 in winter). The path loss exponent in Scenario 2b is higher than one in [6] which found as 1.68, and

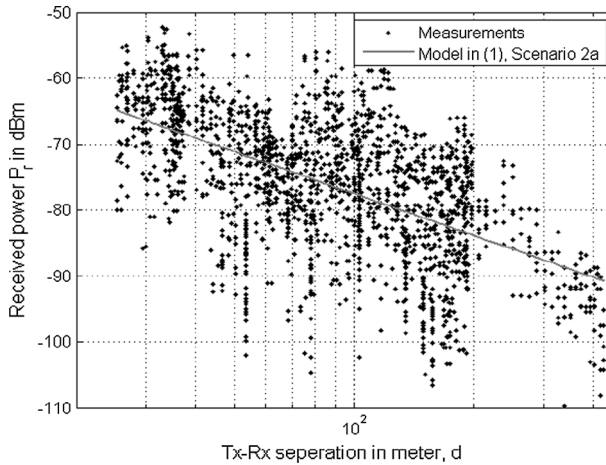


Fig. 6 Received power and path loss for Scenario 2a

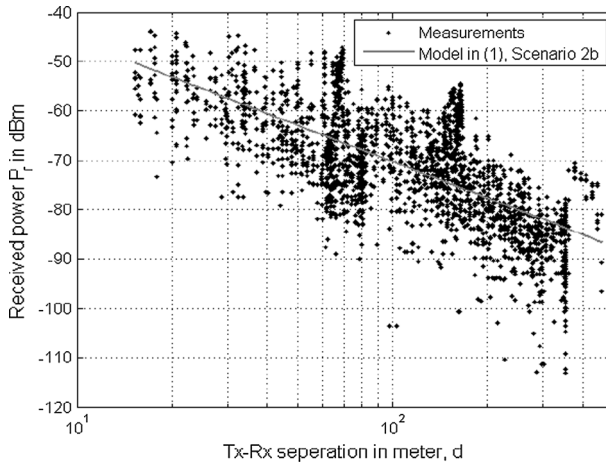


Fig. 7 Received power and path loss for Scenario 2b

$P_L(d_0)$ is close to one in [6] which is 62.0 dB if the VL is taken into account for the Tx and Rx antennas [7, 8, 22].

3.3 Scenario 3

As shown in Fig. 8, the path loss exponent and reference path loss are, respectively, $n = 3.44$ and $P_r(d_0) = -40.33$ dBm. The value of n in Scenario 3 suggests that the path loss fading for Scenario 3 is slightly more severe than ones in Scenarios 2a and 2b.

Standard deviations of shadowing as shown in Table 1 is found to be in the range of 3.57~4.87 dB. In [18] κ was reported as 5.5 dB for data set 1; and 7.1 dB for data set 2. From measurements, we have made the following observations for shadowing: (1) The standard deviation κ is found to be smaller in Scenario 1 than Scenario 2a. This suggests that the wall of trees and bushes in the urban test area created a more dense environment than forest

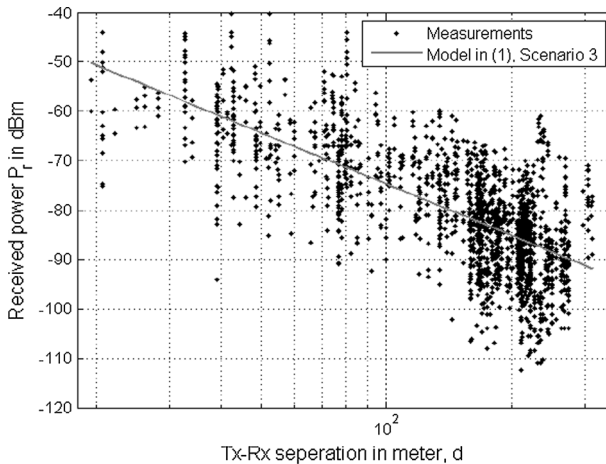


Fig. 8 Received power and path loss for Scenario 3

trees; (2) κ is found to be very close for Scenario 2a and 2b. The minor difference can be explained by island in between the two lanes which may partly blocked the path while moving in opposite directions; This is in contrast to Scenario 2a where the ground was even between the Tx and Rx; (3) In Scenario 3, it was noticed that κ was lower than κ for Scenario 2b. This is expected as the body size of the tester is much smaller than the test vehicle.

4 Conclusions

We presented IV2IV and IV2W channel measurements, capturing the effect of having the mobile station inside the vehicle, in forest/woody and urban areas with dense scattering environments. Three test scenarios were presented classified by location and test setup. The proposed empirical path loss models are obtained from the measurements. Proposed models in forest have a lower error than the conventional stationary models. Single-slope path loss models are studied for all urban scenarios. Depending on the test scenario, the path loss exponents in the dual-mobility channels are found between 2.1 and 8.0, and the reference path loss is found to be larger due to the placement of the antenna inside the vehicle.

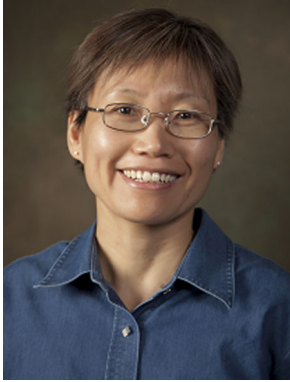
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